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Geospatial Analysis of Terrain Stability for Sustainable Development Planning in Chamoli District, Uttarakhand

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Abstract

Landslides, slope failure, flashflood are common phenomena in the Himalayan region and severely affect human settlements, transportation infrastructure and natural ecosystems. Therefore, assessing terrain stability is crucial for sustainable habitation and development planning. The present study evaluates terrain stability zones in the Chamoli district using the Analytical Hierarchy Process (AHP) integrated with Geographic Information System (GIS) techniques. A great variety of terrain stability is observed in the study area. By the combined effect of five parameter i.e. landslide zones, slope, tectonic unit, altitudinal zone and snow affected area the final terrain stability map have been prepared which is classified into four zones, namely very stable, stable, moderately vulnerable and highly vulnerable. Very stable terrain (10.19%) is observed in the southern, south-eastern and middle-western part and stable terrain (16.63%) is observed in the middle eastern, middle western and southern part the study area. The moderately vulnerable and highly vulnerable terrain are observed at 33.35% and 39.83% in the study area respectively.

Keywords: *Chamoli District, Terrain Stability zones, Analytical Hierarchy Process (AHP), Geographical Information System (GIS).*

Introduction

Due to highly dissected terrain and different type of natural calamities such as landslide, flashflood people always try to settle in plain land, but now adays due to rapid population growth human beings are forced to settle in the hilly region. The rapid population growth demanded the use of areas which were not previously used for settlement, urban expansion, agricultural and other purposes thereby exposing these areas to landslide problems after rainy seasons (Temesgen et al.2001; Abebe et al.2010; Woldearegay, 2013). Unscientific construction of settlement, roads and industries trigger the instability of terrain. Identification of stable terrain is most important for the construction of roads, buildings. Terrain stability zones indicate the areas of slope stability with respect to stable, potentially unstable and unstable terrain within a particular landscape delineating the zones of slope failure (Forest practices code of British Columbia 1999).

At present different type of interdisciplinary decision-making approaches used to determine the terrain stability zone. Among them Analytical hierarchy process (AHP) is one of them. The application of AHP was first introduced by Saaty in 1980. It is an approach using different types of multi-criterion, which focuses on the relative priorities assigned to each criterion to achieve a defined objective. (Nandy, 2021). AHP is widely used to identify environmental suitable zone, tourism potential area, landslide susceptibility zone, agricultural suitability area, land suitability area etc. Many scholars use this techniques in the different field of study, such as Akinei, *et al.,*2013, Pramanik, 2016,Yalew, et al.,2016, Khan, et al., 2022, Veisi, et al 2022, and others. (For delineating suitable agricultural land), Thiyagarjan and Subbarayan, 2022, Agarwal, et al., 2013 and other (For identify ground water potential zone), Cengiz and Akbalak,2009, Patil et al. 2012, Memarbashi, et

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al., 2017, Kumari et al.,2010,Bunruamkaew and Murayama, 2011 and others (for identify suitable ecotourism site).

The present study analyses the geological, geomorphological and environmental parameters which influence terrain stability in the Chamoli District. **The primary objective of this study is to prepare a terrain stability map using selected parameters and the AHP-GIS techniques, to delineate and classify the study area into different stability zones and to identify potential areas suitable for sustainable human settlement and developmental planning.**

Study Area

Chamoli district, a part of the Garhwal Himalaya, is located between 29°55′37″ to 31°27′03″ North latitude and 78°54′03″ to 80°02′03″ East longitude, covering an area of about 8,030 km². Geologically, the region is predominantly composed of the Jaunsar Series and Simla Slates, while the north-eastern part consists of the Martoli Series, Garbyang Series and other unclassified Himalayan rocks. Additionally, patches of the Lilang System, Pir Panjal Trap, granites and volcanic deposits are found in the district. Physiographically, Chamoli exhibits highly undulating terrain with an altitudinal range from about 680 m to 7,817 m above sea level, encompassing snow-free valleys as well as towering peaks with permanent snow cover and glaciers. Climatically, the mean monthly temperature ranges from 9.39°C in January to 24.53°C in May. The district also experiences significant variation in rainfall, with mean monthly precipitation ranging from as low as 0.5 mm in October to as high as 454.6 mm in August.

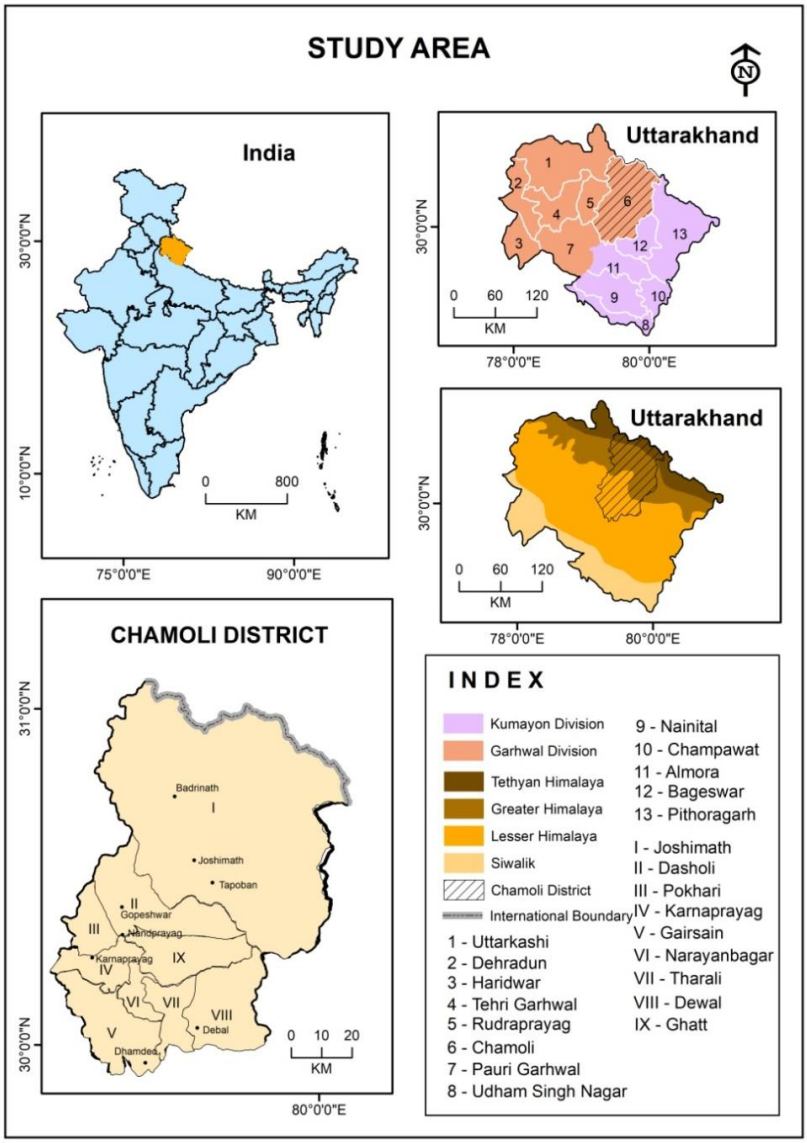

Figure 1. Location map of the study area

Database and Methodology

The primary objective of this study is to identify terrain stability zones within the study area. Initially, primary data were collected through Global Positioning System (GPS)–based field surveys, along with interviews with experts and local residents to determine the most relevant factors influencing terrain stability. In addition, secondary data- including satellite imagery, GIS datasets, research articles and previous records- were obtained from various sources. The datasets used in this study are listed in Table 1.

Table 1. Characteristics of used datasets

Data	Scale/resolution	Date of acquisition	Source
Topographical maps	1:50000	-	Survey of India (SOI)
AlosPalsar DEM	Spatial resolution: 12.5 m	18/11/2018	www.asf.alaska.edu
Landslide data	1: 20,00,000	15/03/2022	National Disaster Management Authority (NDMA), Uttarakhand
Geology & Tectonic	1:333000	-	Works of Valdiya (1976 & 1979) & Sharma et al (2017).

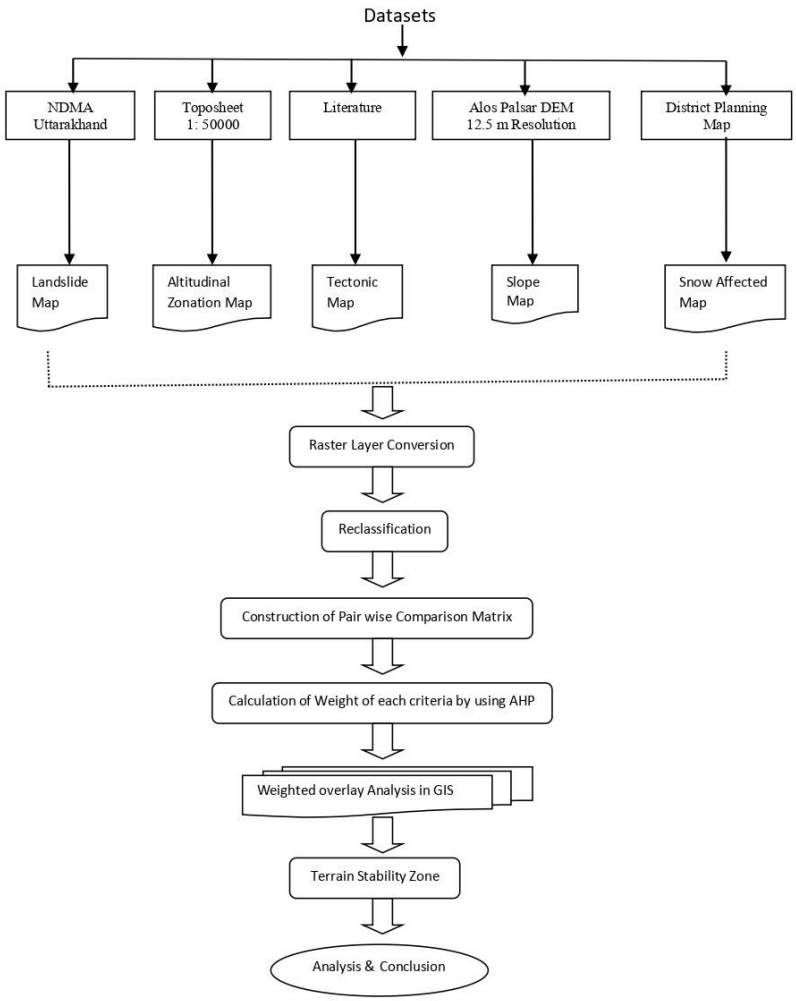

Figure 2. Flow chart of the research work

The selected parameters and their thematic layers were prepared with the help of Microsoft excel v. 2016 and ArcGIS 10.5 software. It helps in accurate delineation and analysis of terrain features aided by methods of applied geomorphological studies (Patra et al, 2021). Slope map have been prepared from Alos Palsar DEM by using spatial analysis tools in ArcGIS environment. Altitudinal zonation map have been prepared from Survey of Indi Toposheet (1:50000).

The final terrain stability map has been prepared through AHP method in ArcGIS 10.5 software. For the preparation of terrain stability map, following the major steps –

i) At first choose the suitable parameter /criteria
ii) Calculate weight of each criteria and sub-criteria
iii) Generate terrain stability map

Selected parameters & their reclassification

To identify the stable terrain, the first step is selection of suitable parameters. In this study five different parameters were used, these are- landslide prone area, slope, tectonic unit, snow affected area and altitudinal zone.

Landslide-prone areas

Being the youngest mountain system of the world, it constitutes a fragile ecosystem of unstable slopes, giving rise to frequent geo-hazards including landslides (Chauhan et al, 2010). The landslide prone zonation map of the study area was prepared using data obtained from the National Disaster Management Authority (NDMA), Uttarakhand. Initially, the base map was georeferenced to the WGS-84 datum and projected into the UTM coordinate system. Subsequently, the map was digitized in ArcGIS 10.5 to delineate three landslide-prone zones- moderate to low, high and severe to very high- within the study area. These zones were then ranked based on their relative terrain stability.

Slope

There is a positive relationship between slope and erosion. It is an important parameter to determine the terrain stability zones in the study area. It is the first derivative of elevation with each pixel denoting the angel of slope at a particular location. (Saha, et al. 2002). The greater inclination of the slope tends to move under the force of gravity nullifying the shearing strength of the component materials in situ (Bhattacharya, 2020). Drainage network may adversely affect slope stability by toe undercutting or by saturating the slope forming material (Kundu et al, 2013). In Himalayan terrain, the south facing slopes are generally more susceptible to slope failure as compared to north facing slopes because they are devoid of vegetation or are scantily vegetated (Sinha et al. 1975). The slope map of the study area prepared from Alos Palsar DEM (12.5) by using spatial analysis tool in ArcGIS 10.5 software. On the basis of slope, the study area is divided into five zones, these are- <25°, 25° – 30°, 30° - 35°, 35°- 40° and >40°. Among them <25° and 25° – 30° slope area is least vulnerable and suitable for human habitation. On the other hand 35°- 40° and >40° slope zone are more vulnerable due to glacier cover and less soil resistance.

Altitudinal Zone

Altitudinal zones of the study area are prepared on the basis of contour line. On the basis of altitude the whole district is classified into six groups at an equal interval of 1000 m. these are < 2000m, 2000m-3000m, 3000m-4000m, 4000m-5000m, 5000m-6000m and >6000m. These are further reclassified into five categories. The elevation of the study area increases from the south-west to the north-east, accompanied by a corresponding decrease in terrain stability. Figure 3,c shows about 40% of the study area included low altitudinal zones resulting high terrain stability and suitable for settlement development.

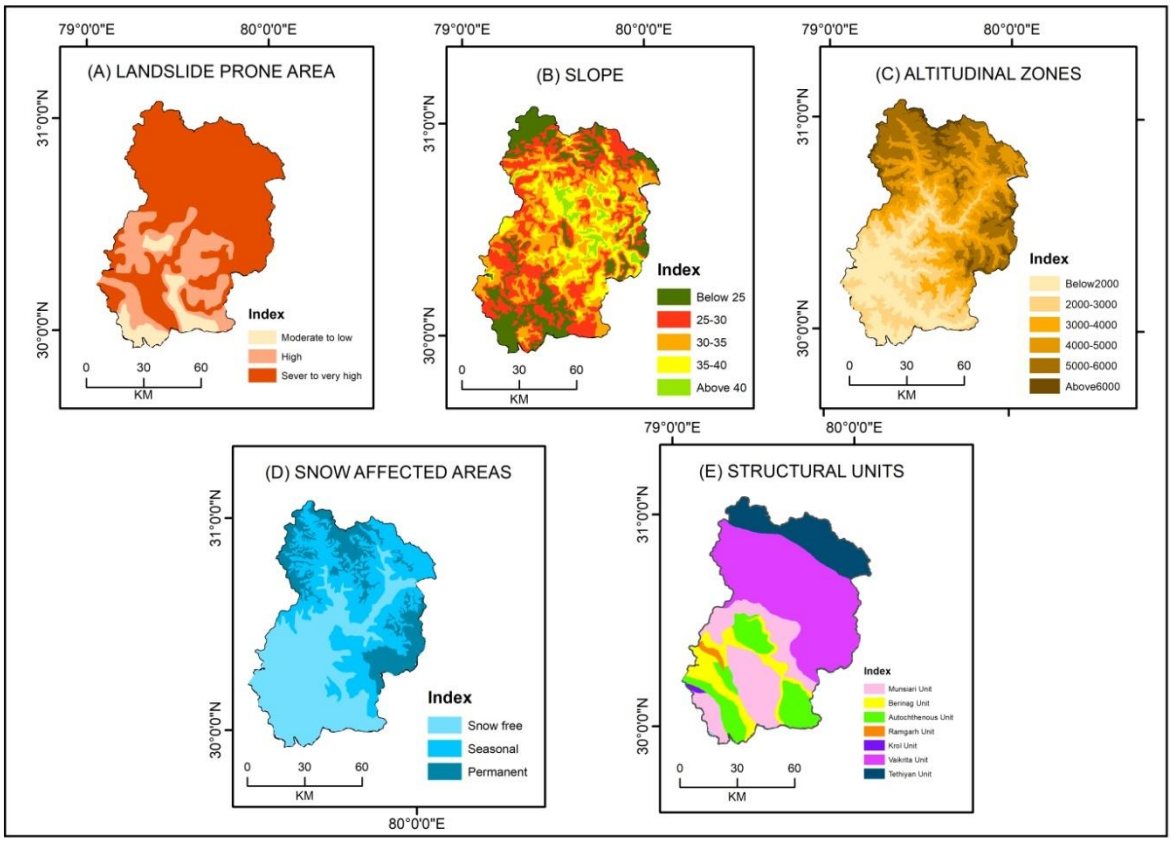

Figure 3. Reclassified parameters, A) Landslide prone areas, B) Slope, C) Altitudinal zones D) Snow affected area and E) Structural units

Snow Affected Area

Snow cover and glaciers significantly influence both the stability and vulnerability of an area by promoting physical weathering and triggering avalanches. The eastern, north-eastern, northern, north-western and western parts of the study area are characterized by permanent glacier cover, which increases overall vulnerability.

Based on snow cover conditions, the study area is classified into three zones: permanent glaciated, seasonal glaciated and non-glaciated areas. The non-glaciated zone, covering approximately 42% of the total area, is assigned a rank of 1, indicating relatively higher stability. The seasonal glaciated zone accounts for about 39% of the area and is assigned a rank of 2. The permanent glaciated zone, occupying around 19% of the total area, is ranked 3, reflecting the highest level of vulnerability.

Structural Unit

The underground geological formation and structural lines affect the occurrence of landslides as well as the terrain stability to a certain extent (Gokceoglu and Aksoy 1996; Cha and Kim 2011; Ahmed and Akram 2018; Bhattacharya 2020). Seven structural units have been identified within the study area: Munsiyari, Autochthonous, Berinag, Ramgarh, Krol, Vaikrita, and Tethyan units. These units were further reclassified into five categories and assigned ranks from 1 to 5 based on their relative stability. The tectonic map of the study area had been prepared on the basis of the work of Valdiya (1976 & 1979), Sharma et al (2017). At first the main map are georeferenced and converted into WGS 84 datum and UTM projection, after that digitize the map to sketch the structural units. (Figure. 3)

Calculation of Weight for each criterion

To solve any kind of decision making problem through AHP model, prioritization of the criteria by 'pair wise comparison' of all the selected layers are taken into consideration. (Nandi, 2021, p. 232) Here every parameter is compared to each other by imposing relative value between 1 to 9. In the present study Saaty's fundamental scale for degree of importance has been used.

Table 2. The fundamental scale for degree of importance

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Essential or Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgement	When compromise is needed

In the 'pair wise comparison matrix' each criterion is related against another criterion in the hierarchical order between 1 to 9 (where criteria of row became important over column) and between 1/2 to 1/9 (where criteria of column become important over row). Using the pair wise, the analytical hierarchy process calculates comparative weights for individual criterion layers. (Yalew, t al., 2016, p. 08)

Acceptability of the matrix table has been checked through the Consistency Ratio (CR). The value of the CR is measured through the following formula –

$$CR = CI/RI$$

Where, CI is the Consistency Index and RI is the Random Index of hierarchical order of the matrix. The formula of the CI is

$$CI = (\lambda max - n) / (n - 1)$$

Where, λmax is the principle or highest eigenvector of the matrix and n indicates the order of the matrix. For meaningful result the value of CR must be smaller than 0.10 (Saaty, 1977). Weights or priorities are determined by normalizing the pair wise comparison matrix (Akinci, *et al.*,2013, p. 6)

Table 3. Pairwise comparison matrix

Criteria/Parameters	Landslide Zones	Slope	Altitudinal Zone	Snow Affected Areas	Structural Unit	Weights
Landslide Zones	1	3	4	6	8	0.491
Slope	0.33	1	3	5	7	0.276
Altitudinal Zone	0.25	0.33	1	2	4	0.122
Snow Affected Areas	0.17	0.20	0.50	1	3	0.074
Structural Unit	0.12	0.14	0.25	0.33	1	0.0370

Max. eigenvalue (λmax) = 5.193

n = 5

Consistency index (CI) = 0.04825

Random index (RI) = 1.12

Consistency ratio (CR) = 0.0430

Table 4. Normalized value of cumulative weight (Cw)

Criteria/Parameters	Landslide Zones	Slope	Altitudinal Zone	Snow Affected Areas	Structural Unit	Sum
Landslide Zones	0.5347	0.6423	0.4571	0.4187	0.3478	2.4006
Slope	0.1764	0.2141	0.3428	0.3489	0.3043	1.3865
Altitudinal Zone	0.1336	0.0706	0.1142	0.1395	0.1739	0.6318
Snow Affected Areas	0.0909	0.0428	0.0571	0.0697	0.1304	0.3909
Structural Unit	0.0641	0.0299	0.0285	0.0230	0.0434	0.1889

Normalized value of each sub criterion of every parameters has been calculated through rank normalization. Determination of rank score of every sub criterion on the basis of 'Likert scale' where rank is assigned with in 5 responses in numerical value to measure the characteristics of stability of sub criteria under investigation. Here, highest rank represents greater terrain stability and vice-versa. At last rank normalization value is multiplied with parameters weight to get the normalized value of each sub-criteria. After getting normalized value of each sub-criteria then add the values in the attribute table and prepared terrain stability map by using weighted overlay tool in ArcGis 10.5.

Table 5. Normalized value of each sub-criteria of parameters

Criteria/ Parameters	Sub-Criteria	Parameter Weight	Rank	Rank Normalization	Normalised Value	Area in Km²
Landslide Zones	Moderate to Low	0.491	1	0.1667	0.0818	657.05
	High		2	0.3333	0.1636	1824.27
	Severe to Very High		3	0.5000	0.2455	5548.68
Slope	< 25º	0.276	1	0.0667	0.0184	1525.14
	25º - 30º		2	0.1333	0.0367	2578.70
	30º - 35º		3	0.2000	0.0552	2371.95
	35º - 40º		4	0.2667	0.0736	1268.93
	> 40º		5	0.3333	0.0919	285.28
Altitudinal Zone	< 2000 m	0.122	1	0.0476	0.0058	1571.80
	2000 m - 3000 m		2	0.0952	0.0116	1657.60
	3000 m - 4000 m		3	0.1428	0.0174	1142.18
	4000 m - 5000 m		4	0.1904	0.0232	1679.49
	5000 m - 6000 m & > 6000 m		5	0.2380	0.0290	1978.93
Snow Affected Areas	No Glaciated Zone	0.074	1	0.1667	0.0123	3424.54
	Seasonal Glaciated Zone		2	0.3333	0.0246	3128.82
	Permanent Glaciated Zone		3	0.5000	0.0370	1476.64
Structural Unit	Munsiyari Unit	0.0370	1	0.0666	0.0024	1766.89
	Autochthenous Unit		2	0.1333	0.0049	1048.57
	Berinag Unit		3	0.2000	0.0074	759.57
	Ramgarh Unit & Krol Unit		4	0.2666	0.0098	76.45
	Vaikrita unit & Tethiyan Unit		5	0.3333	0.0123	4378.52

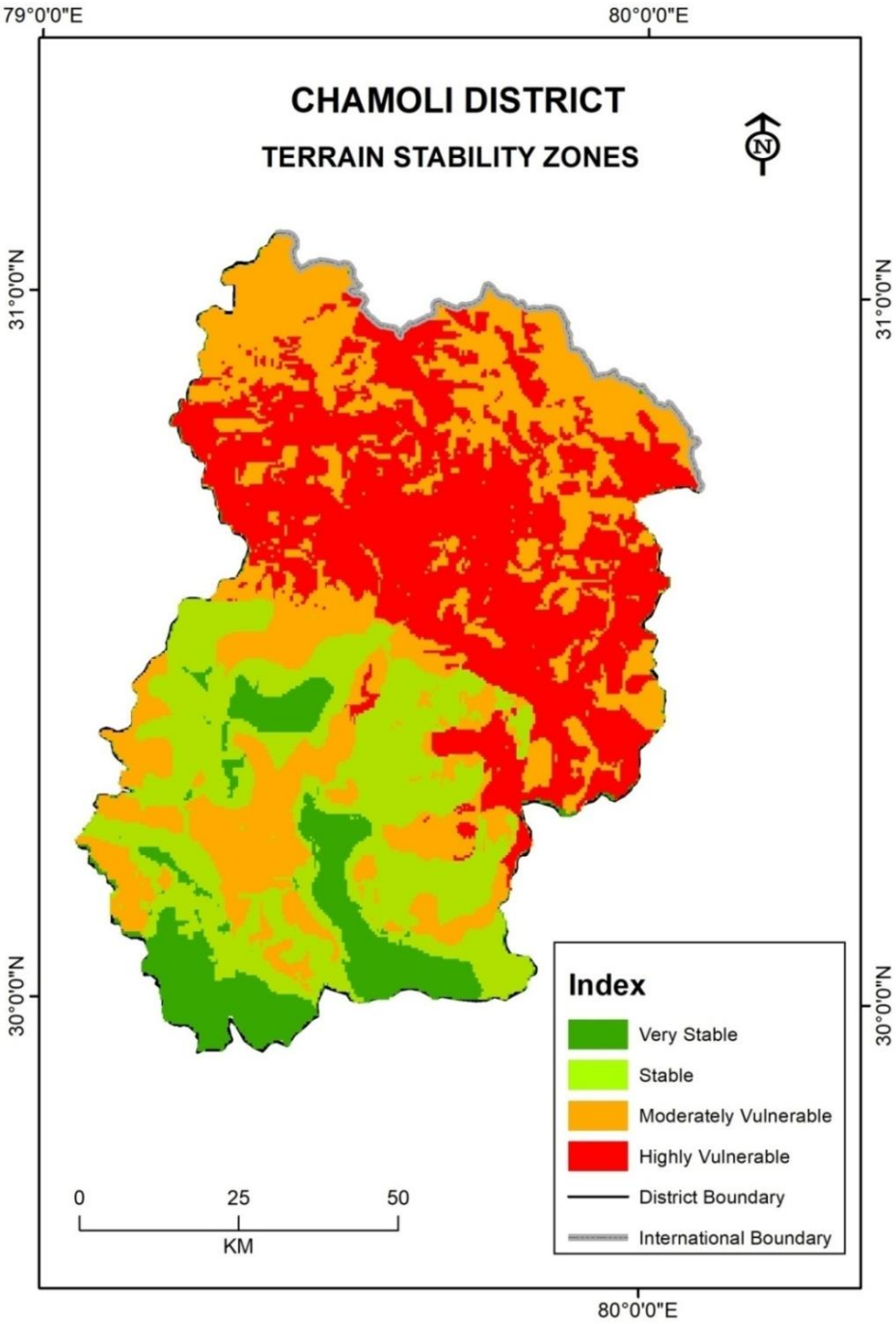

Figure 4. Terrain stability zones of the Chamoli District

Results

The predicted terrain stability map of the study area has been prepared with the help of five parameters i.e. landslide prone area, slope, tectonic unit, snow affected area and altitudinal zones.

Landslide prone area is considered the foremost among them as terrain stability is directly regulated by this parameter (Escape et al, 2015). This map is classified into three vulnerability zones- i) moderate to low, ii) high and iii) sever to very high. Moderate to low zone occupied only 657.05 sq. km. or 8.18% of the study area, observed in the south, south-east and eastern side of the district in a narrow patches, High zone occupied 1824.27 sq. km. or 22.72 % of the study area, observed in the south, middle-east and middle-west of the district, Severe to very high category occupied large area (5548.68 sq. km. or 69.10%) in the district, observed in the north, middle, middle-north, middle-east, middle-west, middle-south of the study area. The total area of the district is classified into five slope categories, these are- i) <25º, ii) 25º -30º, iii) 30º -35º, iv) 35º -40º and v) >40º. These slope zones are unevenly distributed in the different part of the study area. Among

them 25º -30º & 30º -35º slope zone occupied 61.65% of the study area. Very low (<25º) & very high slope zone (>40º) covers 18.99% & 3.56% respectively.

In the study area seven structural unit have been identified, these are Munsiyari, Autochthonous, Berinag, Ramgarh, Krol, Vaikrita, and Tethyan units. Among them, the Munsiyari unit is comparatively more stable, covering approximately 22% of the total area. In contrast, the Vaikrita and Tethyan units are highly vulnerable due to the presence of the Vaikrita Thrust and together they occupy about 54% of the study area. The study area has been classified into three zones based on glaciations- permanent glaciated, seasonal glaciated and non-glaciated zones. The non-glaciated zone, covering approximately 42% of the total area, is mainly located in the southern part of the study area. The seasonal glaciated zone accounts for about 39% of the area and is predominantly found in the middle-eastern, north-eastern and north-western parts of the district. The permanently glaciated zone occupies around 19% of the total area and is primarily distributed across the middle-eastern, northern and north-western regions of the study area. The proportionate relationship between elevation and stability acquires a secure situation in the examination of terrain stability analysis (Pack et al, 2001). On the basis of altitude the study area divided into six classes- i) <2000 m (19.57%), ii) 2000-3000 m (20.64%), iii) 3000-4000 m (14.22%), iv) 4000-5000 m (20.94%) , v) 5000-6000m (20.64%) and vi) >6000 m (2.99%). The elevation of the study area increases from south to north and middle to east and instability also increased proportionally.

Assessment of Terrain stability zones

The terrain stability map of the study area has been prepared on the basis of the weight of the different thematic layer and their classes in GIS environment. The final map of the terrain stability has been classified into four zones using the quintile classification method. The classified terrain stability zones of the study areas are- very stable, stable, moderately vulnerable and highly vulnerable which covers 818.84 km², 1335.70 km², 2678.40 km² and 3197.06 km² area respectively. (Table 6)

Table 6. Summary of terrain stability map of the study area

Terrain Stability Zones	Area	
	(In Sq. Km.)	(In %)
Very Stable	818.84	10.19
Stable	1335.70	16.63
Moderately Vulnerable	2678.40	33.35
Highly Vulnerable	3197.06	39.83
Total	8030	100

The very stable zone observed in the south, south-west and lower middle western side of the district as a narrow patches. It occupied 818.84 sq. km. or 10.19% of the total area.(Table 6) Table 6 also reveals that the stable zone occupied 1335.70 sq. km or 16.63% of the total area, this zone is mainly observed in the south-west, south-eastern, middle-west, lower- middle-eastern portion of the district. These two zones are mainly suitable for settlement development. Moderately vulnerable zones are observed in the middle- south, middle-east, middle-west and some small patches in the northern portion of the district. Presence of glacier, high altitudinal mountains, highly dissected topography makes the middle north, north, north-eastern and north-

western portion of the district is highly vulnerable. It occupies the largest area of the district. (3197.06 sq. km. or 39.83% of the study area) High physical weathering resulting in rock fall, landslide, avalanches are the common phenomena in this region. For that reason human construction are impossible in this region, only some settlements have developed for religious purpose and some seasonal settlements have developed for tourism purpose.

Conclusion

The present study demonstrates the effective integration of the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) techniques to assess terrain stability zones in the Chamoli district of the Garhwal Himalaya. The terrain stability of the study area is strongly influenced by diverse geological, geomorphological and environmental factors. Five key parameters- landslide susceptibility, slope, tectonic units, snow cover and altitude- were utilized to prepare the terrain stability map.

The final map delineates four distinct stability zones- very stable, stable, moderately vulnerable and highly vulnerable. The results indicate that very stable (10.19%) and stable (16.63%) zones are mainly concentrated in the southern, south-eastern, and central parts of the study area. These regions are less affected by tectonic disturbances, steep slopes, and snow cover, making them more suitable for human settlements and associated activities such as agriculture, markets, religious sites and transportation networks. In contrast, the eastern, north-eastern, northern, and north-western parts of the district are classified as highly vulnerable (39.83%) due to high relief, steep slopes, and greater landslide susceptibility. A clear spatial trend of decreasing vulnerability from north to south is observed, reflecting the influence of topographic gradients and lithological variations. Among the selected parameters, slope, landslide susceptibility and tectonic structures emerge as the most significant factors controlling terrain stability in the Himalayan region.

Overall, the integration of AHP and GIS proves to be an effective approach for evaluating terrain stability and identifying suitable zones for infrastructure development and disaster risk reduction. The findings of this study can assist engineers, policymakers and regional planners in formulating sustainable land-use strategies and mitigating geomorphic hazards in the Chamoli district and similar Himalayan environments.

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